

# Finding Planets Around White Dwarf Remnants of Massive Stars

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## ABSTRACT

Planet frequency shows a strong positive correlation with host mass from the hydrogen-burning limit to  $M \sim 2 M_{\odot}$ . No search has yet been conducted for planets of higher-mass hosts because all existing techniques are insensitive to these planets. We show that infrared observations of the white-dwarf (WD) remnants of massive stars  $3 M_{\odot} \lesssim M \lesssim 7 M_{\odot}$  would be sensitive to these planets for reasons that are closely connected to the insensitivity of other methods. We identify 49 reasonably bright, young, massive WDs from the Palomar-Green survey and discuss methods for detecting planets and for distinguishing between planet and disk explanations for any excess flux observed. The young, bright, massive WD sample could be expanded by a factor 4–5 by surveying the remainder of the sky for bright UV-excess objects.

*Subject headings:* planets – white dwarfs – massive stars

## 1. Introduction

Extrasolar planets have been discovered by 4 different techniques orbiting stars ranging from the hydrogen-burning limit to about 2.5 solar masses. As first pointed out by Laws et al. (2003), the fraction of monitored stars that are found to have planets climbs steadily as the host mass increases from  $0.75 M_{\odot}$  to  $1.5 M_{\odot}$ . Fischer & Valenti (2005) found a more significant trend in a larger sample and noted that while this might reflect a higher rate of planet formation around massive stars, it could also be an indirect selection effect due to the known correlation between planet frequency and metal abundance, combined with the fact that their sample shows a strong correlation between stellar mass and metallicity. Johnson et al. (2007) extended this correlation to the entire observed range of host masses  $0.1 M_{\odot} < M < 1.9 M_{\odot}$  (considering only planet masses  $m > 0.8 M_{\text{jup}}$  and semimajor axes  $a < 2.5 \text{ AU}$ ) and argued that it was in fact independent of the correlation of frequency with metallicity.

It would be quite interesting to determine whether the correlation of planet frequency with host mass continues to yet higher masses. However, current techniques are extremely challenged in the regime  $M \gtrsim 3 M_{\odot}$ . Radial-velocity (RV) searches are restricted to FGKM stars because of the absence of usable lines in earlier-type stars. RV searches have managed an “end run” around this problem for stars of 1–3  $M_{\odot}$  by monitoring the *red giant descendants* of these early type stars (Frink et al. 2002; Reffert et al. 2006; Johnson et al. 2007; Lovis & Mayor 2007). Reasonable mass estimates can be obtained from spectroscopic gravities, although these are not quite as accurate as the mass estimates of main-sequence (MS) stars.

Massive red giants still pose significant challenges for the RV technique. Their low gravities induce atmospheric instabilities, which radically degrade RV precision relative to what is possible for stable MS stars. So far, this reduced precision has limited searches to relatively massive planets with periods of order a few hundred days, i.e., well inside the “snow line” that is believed to be the boundary of massive-planet formation. Hence, these searches probably probe only migrated planets and so provide a much smaller window than is available for less massive stars.

At yet higher masses, this technique becomes less effective: declining stability of the red-giant atmospheres and increasing stellar mass both tend to decrease the size of orbits that can be probed, while increasing red-giant radii remove close-in planets. Finally, the declining mass function and declining lifetime both tend to reduce the overall population of hosts. To date, there are no planets detected with host masses  $M > 2.5 M_{\odot}$ , although Lovis & Mayor (2007) did find a low-mass brown dwarf orbiting a star with  $M = 3.9 M_{\odot}$ . Figure 1 is a color-magnitude diagram of all hosts detected by the RV, transits, and microlensing as of June 2007. Figure 2 shows the mass of these planets vs. the mass of their host stars.

The transit technique is challenged to detect planets around massive stars for three reasons: first they are big, second they are rare, and third (most critically) there is no way to confirm detections. In principle, the first problem could be overcome by more accurate photometry, which would probe the smaller fractional transits caused by large stellar radii. Lack of targets is a more fundamental problem, since even very large surveys are detecting relatively few transiting planets even around much more common stars. So, in practice, selection pressure drives this technique to a relatively narrow range of F and G stars (see Fig. 1). But the key problem is that if a planet were detected, the same line-lacunae that plague RV in this mass range would make confirmation extremely difficult. Perhaps with prodigious effort, late M-dwarf “Jupiter impersonators” could be rejected, but the planets could not be reliably distinguished from brown dwarfs, nor could their masses be measured.

Microlensing is often said to be insensitive to host mass, and indeed Figure 1 shows

that microlensing host masses trace the MS mass function: low mass hosts dominate. However, this very fact makes microlensing relatively insensitive to high-mass hosts, just exactly because of their low frequency of birth and early demise. Moreover, microlensing’s “insensitivity to host mass” is predicated on the fact that all potential GKM hosts are fainter (or at least not much brighter) than the bulge sources (which are typically turnoff stars, with some subgiants and giants). By contrast, massive stars are substantially brighter than typical microlensed sources, greatly reducing the probability that the underlying microlensing event could be detected at all under the “glare” (Einstein 1936) of the lens.

Of course, 3 planets have been detected around a pulsar (Wolszczan 1991), which is a remnant of a massive star,  $M > 8 M_{\odot}$ . However, it is difficult to see how planets could survive a supernova explosion without becoming unbound, so these planets are believed to have formed out of an accretion disk generated by fallback from the explosion. Thus, while an extremely interesting system, the pulsar planets probably do not provide any direct information on planets around massive stars.

## 2. A New Approach: Massive White Dwarfs

The very factors that make it difficult to find planets around massive stars  $3 M_{\odot} \lesssim M \lesssim 7 M_{\odot}$ , actually facilitate their detection when the hosts have evolved into white dwarf (WD) remnants. Their short MS lifetimes imply that their planets are still relatively hot (and so luminous) at the time they become WDs. The WDs inherit the huge reservoir of heat of their progenitors, making them both luminous and blue, both of which facilitate their discovery as “contaminants” in magnitude-limited quasar surveys. Finally, these relatively massive WD remnants are physically small ( $r_{\text{WD}} \sim r_{\oplus}$ , Hamada & Salpeter 1961), which sharply limits their luminosity in the infrared (IR), where the planet spectrum peaks.

The range of original periods that can survive the conversion of a massive star into a white dwarf is roughly  $4 \text{ yr} < P_{\text{orig}} < 10^4 \text{ yr}$ , corresponding roughly to semi-major axes  $3.5 \text{ AU} < a_{\text{orig}} < 1000 \text{ AU}$  (Villaver & Livio 2007). For smaller orbits, the planet will be swallowed by its host during its red giant phase. For larger orbits, the planet will become unbound because the star can eject half its mass on timescales of roughly  $10^4 - 10^5$  years (depending on mass). At intervening orbital separations, the planet will evolve adiabatically to larger radii according to the formula  $a_{\text{fin}}/a_{\text{orig}} = M/M_{\text{WD}}$ , still an order of magnitude smaller than orbits that could be disrupted by Galactic tides.

### 3. Palomar-Green Sample

To test the feasibility of searching for planets around the WD remnants of massive stars, we have identified 51 hot, young WDs in the mass range  $0.7 M_{\odot} < M_{\text{WD}} < 1.0 M_{\odot}$ , found in the Palomar-Green (PG) survey. Liebert et al. (2005) present a detailed spectroscopic analysis of these WDs for which they obtained accurate mass and age estimates.

According to the models of Burrows et al. (2003), planet luminosity is heavily suppressed at  $3.6 \mu\text{m}$  and  $5.8 \mu\text{m}$ , implying that warm planets will be most easily visible by *Spitzer* at  $4.5 \mu\text{m}$ . We therefore further restrict the PG sample to those WDs above  $20 \mu\text{Jy}$  at  $4.5 \mu\text{m}$ . This eliminates just 2 targets, leaving a sample of 49.

Figure 3 shows the age distribution of these WDs. Here “age” is defined as time since main-sequence (and so presumably planet) birth. Note that the sample is peaked at 300 Myr and that the great majority are younger than 1 Gyr.

Youth is important because it is the young planets that provide the greatest chance of detection. Figure 4 shows planet/WD flux ratio at  $4.5 \mu\text{m}$  as a function of planet mass (vertical axis) and for various ages and WD temperatures, using Burrows et al. (2003) models. A detection requires that the WD IR flux be accurately predicted based on the temperature and angular radius derived from flux measurements at shorter wavelengths, so that the excess flux due to the planet can be inferred from the *Spitzer* measurement. The fundamental limit of the technique is therefore set by the 2% error in the IRAC absolute flux-calibration (horizontal solid line, Reach et al. 2005).

Note that there is potentially good sensitivity to few-Jupiter mass planets for the majority of the WD ages that are shown in Figure 3. Such planet masses are not uncommon among the red-giant targets of RV surveys, which have somewhat lower-mass MS progenitors than these WDs (see Fig. 2). Johnson et al. (2007) find that the Jovian-planet fraction increases from 1.8% for  $0.1 - 0.7 M_{\odot}$  stars to 4.2% for Sun-like stars, to 8.9%, for  $1.3 - 1.9 M_{\odot}$  stars for  $a < 2.5 \text{ AU}$  and  $m > 0.8 M_{\text{Jup}}$ . Of course, the analogs of all of these planets around higher mass stars would be swallowed before they evolved into WDs, and the frequency of planets around massive stars at wider separations is completely unknown. However, if there are comparable numbers at wider separations and if the observed trend continues or even flattens at higher masses, then the PG sample would be expected to contain several detectable planets: roughly  $49 \times 8.9\% \times (\log(13/2)/\log(13/0.8)) = 2.9$ . Here we have assumed a detection threshold of  $m = 2 M_{\text{Jup}}$  and that planet masses are distributed as  $dN/dm \sim m^{-1}$  from the Johnson et al. (2007) threshold to the brown-dwarf limit,  $0.8 < m/M_{\text{Jup}} < 13$ .

The WDs are quite bright,  $V \lesssim 16$ , so obtaining the accurate optical/near-IR photometry required to predict the fluxes in the IRAC bands would be straightforward. Indeed, 41 of

the 49 PG WDs already have SDSS photometry and 47 are detected in  $J$  band by 2MASS.

#### 4. Planets vs. Disks

Of course, an IR excess at  $4.5\,\mu\text{m}$  could have causes other than planets, in particular, circumstellar disks. At present, these alternatives can be easily distinguished by observing the WDs at the other *Spitzer* IRAC bands: warm-planets would only show an excess at  $4.5\,\mu\text{m}$ , while cool-dust emission would be detected in most IRAC bands. In fact, all but one of the WDs with debris disks show excess emission in all 4 IRAC bands (von Hippel et al. 2007; Jura et al. 2007), and the majority of them also show excess in the K-band (Kilic et al. 2006). There is only one WD, G166-58, known to have a debris disk that shows up as an excess redward of  $5\,\mu\text{m}$  (Farihi et al. 2007). After *Spitzer*’s cryogen is exhausted, it will still be possible to differentiate planets from *warm* debris disks since these disks would show excesses both in the  $3.6\,\mu\text{m}$  and  $4.5\,\mu\text{m}$  bands. However, the channel for discriminating between planets and cooler disks will disappear.

The candidates found by “Warm *Spitzer*” from observations at  $3.6\,\mu\text{m}$  and  $4.5\,\mu\text{m}$  can still be distinguished from cool disks in some cases. The median distance of the PG WDs is 68 pc, implying that planets lying at projected separations  $r_\perp \gtrsim 140$  AU would be separately resolved by *Spitzer*. Such planets would be recognized by their lack of optical counterpart (in SDSS for the regions covered by that survey). Because the planet orbit expands by  $a_{\text{final}}/a_{\text{orig}} = M/M_{\text{WD}}$ , i.e., a factor 5–7, these separations correspond to  $a_{\text{orig}} \gtrsim 20 - 25$  AU, which is larger than the orbits of Jovian planets in the Solar System. Moreover, there is a correlation between the ages and distances of the targets. Since the PG survey is magnitude-limited, hotter (younger) objects can be detected at larger distances. The median distances for PG WDs with ages  $\leq 300$  Myr and  $\leq 1$  Gyr are 106 pc and 89 pc, respectively. Hence, planets at orbital separations  $a_{\text{orig}} \gtrsim 35 - 40$  AU would be resolved with *Spitzer* around the WDs younger than 1 Gyr. Kasper et al. (2007) failed to find any planets of  $m > 2 M_{\text{jup}}$  and  $a > 30$  AU around 22 young GKM stars, while Lafrenière et al. (2007) failed to find any at  $a > 40$  AU around 85 young GKM stars. However, the orbits of planets around massive stars could be larger.

The *James Webb Space Telescope* (*JWST*) could in principle confirm most of the WD planets detected by *Spitzer* observations. The *JWST* Near-Infrared Camera (NIRCAM) FWHM at  $4.5\,\mu\text{m}$  is  $\sim 0.15''$ . Since the planet/WD flux ratios at this wavelength must be greater than 2%, resolution at 1 FWHM is feasible. At the median sample distance ( $D = 68$  pc), the minimum allowed orbit  $a_{\text{final}} > 10$  AU (or  $a_{\text{orig}} \gtrsim 2$  AU) corresponds to a slightly bigger angle. Of course, half the WD sample is at greater distances and, depending on orbital

phase and inclination, some planets will be significantly closer than  $a/D$ , but the planets will not necessarily cluster at the closest allowed semi-major axis and brighter planets will be detectable at somewhat closer separations or from the astrometric offset of the combined light as seen in the optical and IR. For example, for flux ratios of 10% and separations of  $0.1''$ , the offset is 10 mas, which is easily detectable.

In the meantime, confirmation would be possible for the younger, more massive planets using  $H$  band adaptive optics observations on large ground-based telescopes. For example, at 300 Myr, a  $m = 5 M_{\text{jup}}$  planet has  $M_H = 19.3$  (Burrows et al. 2003), compared to  $M_H = 11.8$  for its WD host, i.e. a flux ratio of 1000. Even without coronagraphs, such ratios should be resolvable at 5 FWHM, corresponding to  $0.3''$  (Van Dam et al. 2006). However, at 1 Gyr, the same planet is 10 times fainter, while at 300 Myr, a  $m = 2 M_{\text{jup}}$  is almost 100 times fainter. Hence, this approach to confirmation would be extremely challenging for the majority of detectable planets.

## 5. Targets in Other Directions

Figure 5 shows the distribution of the PG sample in Galactic coordinates. The green curve is the locus of  $\delta = -10^\circ$ , the apparent southern boundary of the survey. Evidently, about 1/4 of the sky has been covered. There appears to be a slight tendency toward a lower density of massive WDs near the Galactic pole. Such an under-density is expected. The median distance of the WDs is  $\sim 68$  pc. If this distance were small compared to the scaleheight of the massive WD population, then they should be found isotropically. However, with typical ages (since MS birth) of about 300 Myr, massive WDs should be distributed similarly to A stars, which have a scaleheight of 90 pc (Miller & Scalo 1979). Since this is comparable to the sample distance, we expect some suppression at the poles. This would imply that the fields  $|b| < 30$  will be somewhat richer in massive WDs than the PG survey area. Sixty eight per cent of the massive white dwarfs detected in EUVE and ROSAT all-sky surveys are within  $\pm 30^\circ$  Galactic latitude. Liebert et al. (2005) pointed out that the enhanced density of massive white dwarfs at low Galactic latitudes might be due to some of them being the progeny of B stars in Gould’s Belt.

Of course, it is also possible to survey for fainter WDs, but planet detection will generally be more difficult for these because the WDs are more distant, so their planets will be both fainter and at smaller angular separations from the hosts.

## 6. Discussion

Probing WDs for sub-stellar companions began with brown dwarf searches (Probst 1980; Zuckerman & Becklin 1987; Farihi et al. 2005). Winget et al. (2003) proposed to search for planetary companions from timing residuals of pulsating white dwarfs. Mullally et al. (2007a) reported a possible detection of a planet around a pulsating white dwarf, however follow up observations are required to confirm that the observed change in the pulsation periods is not due to the cooling of the star itself. Burleigh et al. (2002, 2006), Debes et al. (2005, 2007), Livio et al. (2005), Friedrich et al. (2006), and Mullally et al. (2007b) proposed and looked for planetary companions from excess near- and mid-IR emission. Hansen et al. (2006) searched for excess IR emission from disks of very massive WDs,  $M_{\text{WD}} > 1 M_{\odot}$ .

What is specifically new to this paper is the idea of probing the previously unexplored stellar mass regime  $3 M_{\odot} \lesssim M \lesssim 7 M_{\odot}$  by looking for the planets around the WD remnants of these stars. Typical field WDs have masses  $M_{\text{WD}} \sim 0.6 M_{\odot}$  and so have MS progenitors  $M \sim 2 M_{\odot}$ . This is a very interesting mass range, currently probed only from red-giant RV studies, which (as noted above) are restricted in sensitivity to relatively close companions  $P \lesssim 2$  yr. Hence, thermal-excess searches could potentially probe new regimes of parameter space for these stars. The very massive WDs studied by Hansen et al. (2006) are believed to be the result of WD-WD mergers. If planets survived this merger process, it would be both surprising and very interesting. Of course, some of the massive white dwarfs in the PG sample may be the products of WD-WD mergers as well. These mergers would result in rapid rotation rates, which could be measured from the non-LTE cores of the Balmer lines. Massive WDs with planetary companions could be spectroscopically checked for high rotation rates in order to see if they are the products of binary mergers or single star evolution.

The regime we have targeted has not been systematically explored. The Mullally et al. (2007b) sample does contain about a dozen WDs in this mass range, but only a few of these have ages less than 1 Gyr, when planets of a few Jupiter masses can still be robustly detected. We have identified a sample of 49 massive WD targets, the great majority of them young, and suggested that 3–4 times as many could be found in other areas of the sky.

There is no guarantee that the observed correlation between stellar mass and planet occurrence will continue to these higher masses. In fact, Kennedy & Kenyon (2007) suggest that the frequency function declines for  $M > 3 M_{\odot}$ . Only observations can settle this question.

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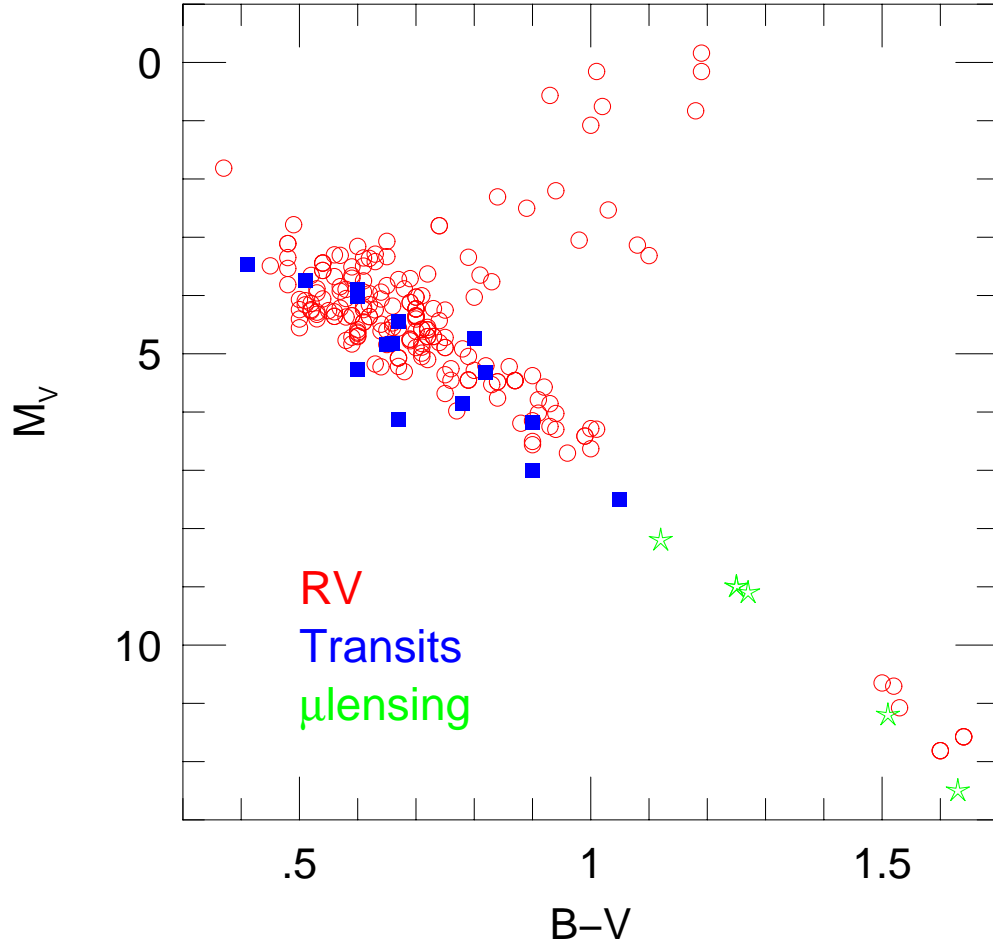


Fig. 1.— Color-magnitude diagram of the host stars of planets detected by the Doppler (RV), transit, and microlensing techniques, as of June 2007.

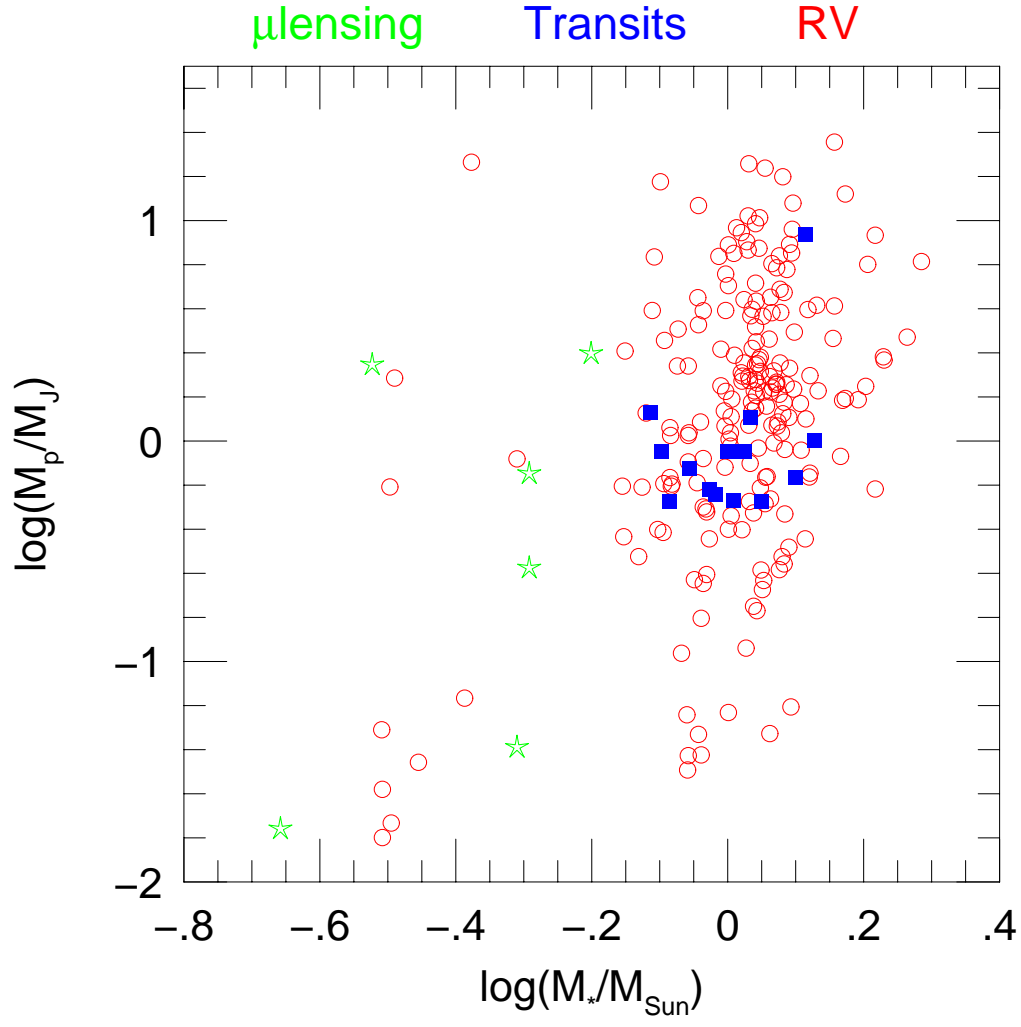


Fig. 2.— Planet mass vs. host mass for the set of targets shown in Fig. 1.

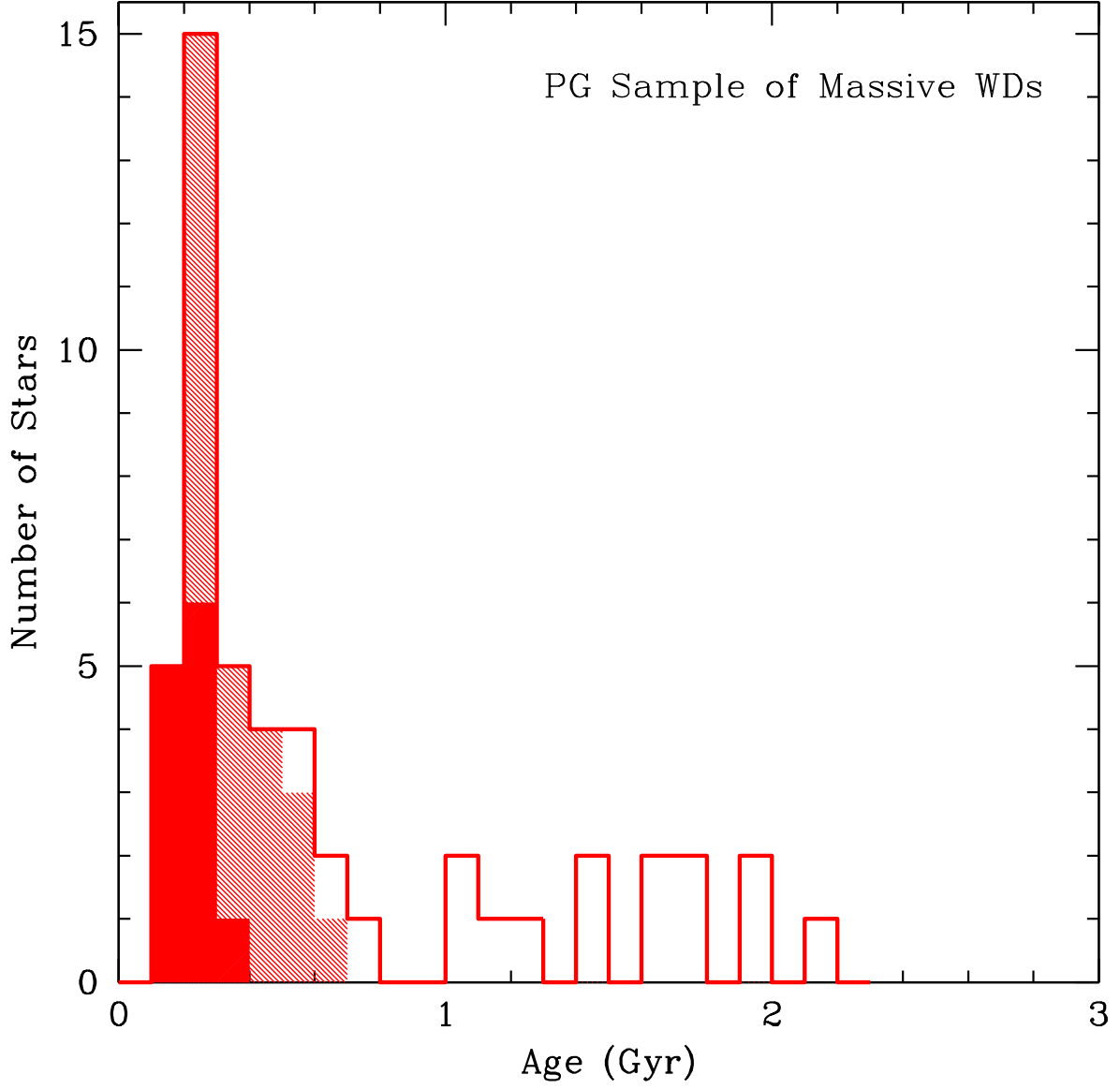


Fig. 3.— Age distribution of WDs,  $0.7 M_{\odot} < M_{\text{WD}} < 1.0 M_{\odot}$  from the PG sample. The contribution from 30000 K, 20000 K, and 10000 K white dwarfs are shown as solid, hatched, and empty histograms, respectively.

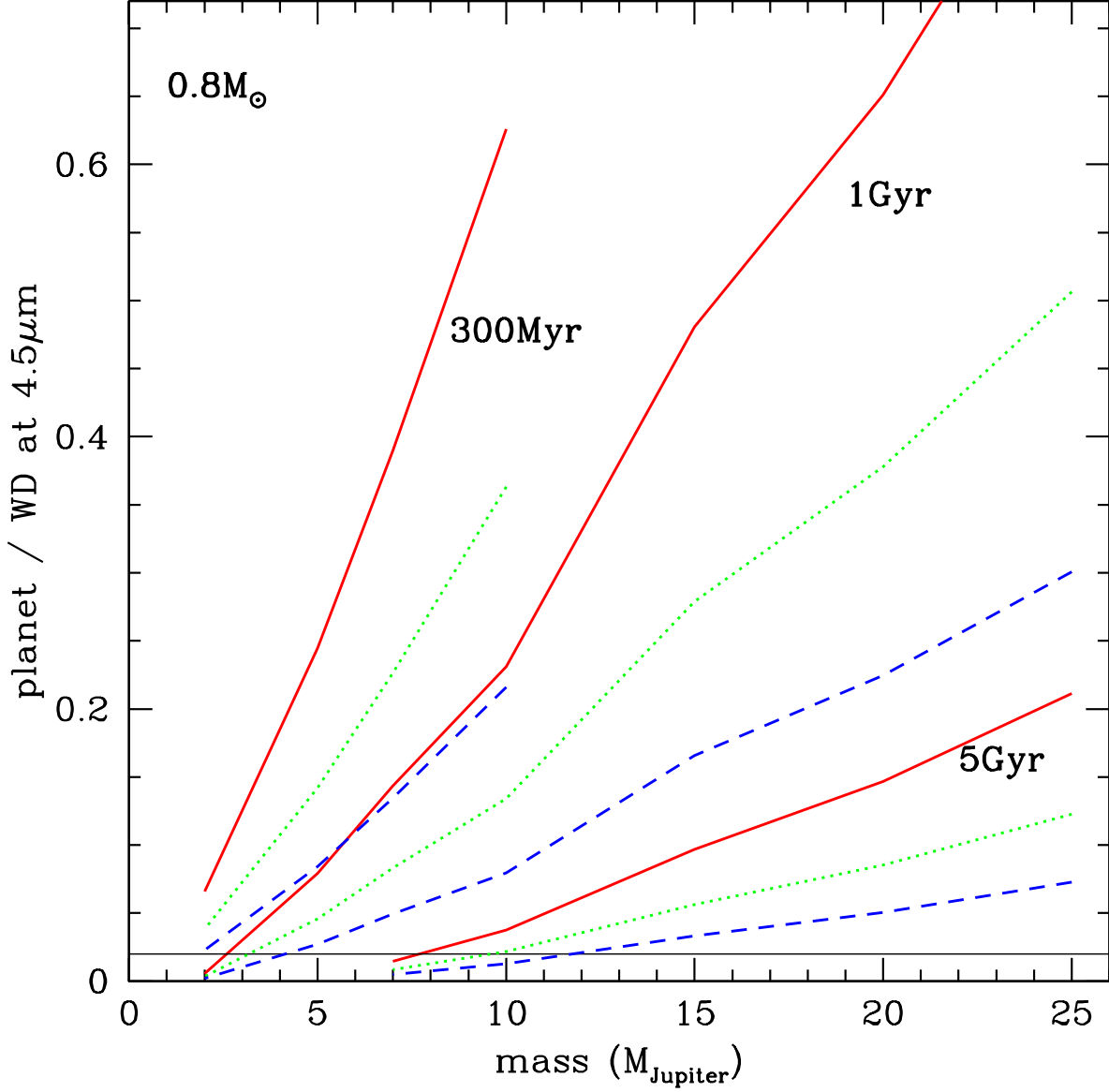


Fig. 4.— Expected  $4.5\mu\text{m}$  excess for planets as a function of mass, at cooling times of 300 Myr, 1 Gyr, and 5 Gyr. The predicted excess for 10000 K, 20000 K, and 30000 K WDs are shown as red solid lines, green dotted lines, and blue dashed lines, respectively. The horizontal black solid line shows the 2% absolute calibration uncertainty for the *Spitzer* IRAC instrument (Reach et al. 2005).

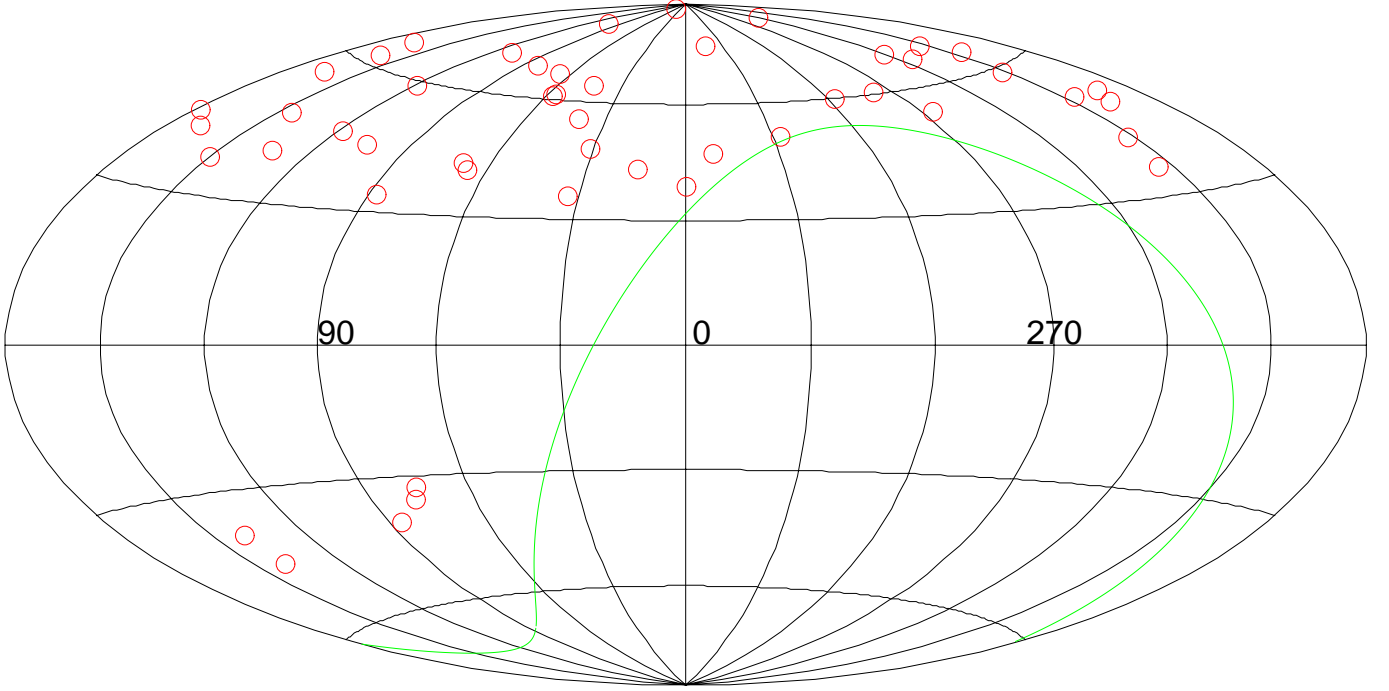


Fig. 5.— Distribution of 49 PG massive WDs in Galactic coordinates. The green curve is at  $\delta = -10^\circ$ , the apparent southern boundary of the survey. Evidently, about 1/4 of the sky has been covered. There is a slight tendency toward lower density near the Galactic pole, implying that the fields  $|b| < 30$  will be somewhat richer in massive WDs than the PG survey area.